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(54) **NON-CIRCULAR CONTACT LENSES WITH PAYLOADS**

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**H04N 13/344** (2018.01)  
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**G02B 27/00** (2006.01)

(52) **U.S. Cl.**  
CPC ..... **G02C 7/04** (2013.01); **G02B 27/0093** (2013.01); **G06F 3/013** (2013.01); **G09G 3/02** (2013.01); **H04N 13/344** (2018.05)

(58) **Field of Classification Search**  
None  
See application file for complete search history.

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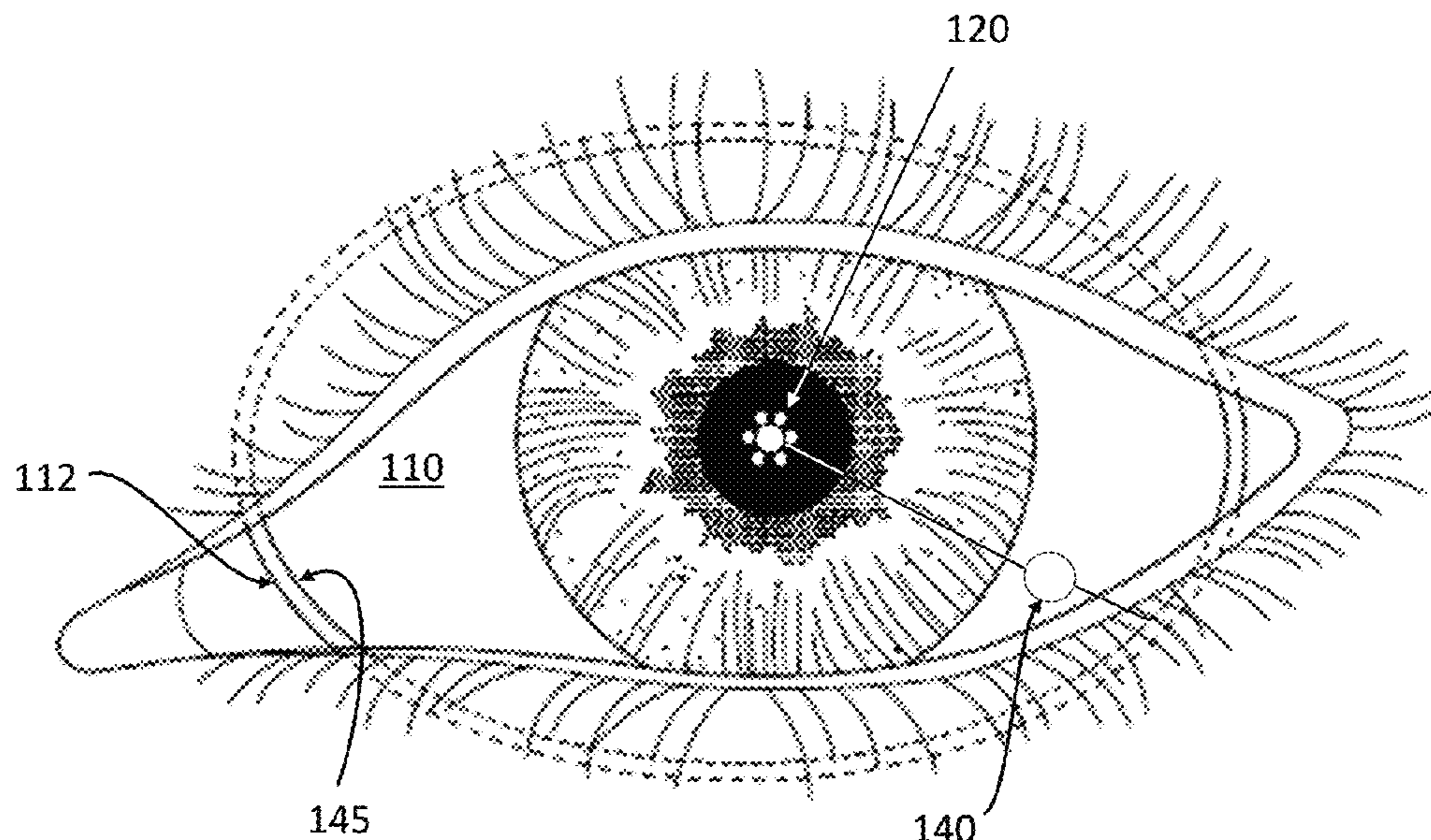
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(57) **ABSTRACT**

An eye-mounted display includes a scleral contact lens with one or more femtoprojectors that project images onto the user's retina. The scleral contact lens has a non-circular perimeter, for example elongated along the direction of the eye opening. The non-circular shape can result in less slippage and/or rotation of the contact lens relative to the eye. If the contact lens is elongated (compared to traditional circular lenses), then it can contain conductive coils that enclose a larger area. Thus, the lens increases coupling efficiency for power or data transfer. There can also be more space within the contact lens for payloads.

**20 Claims, 4 Drawing Sheets**



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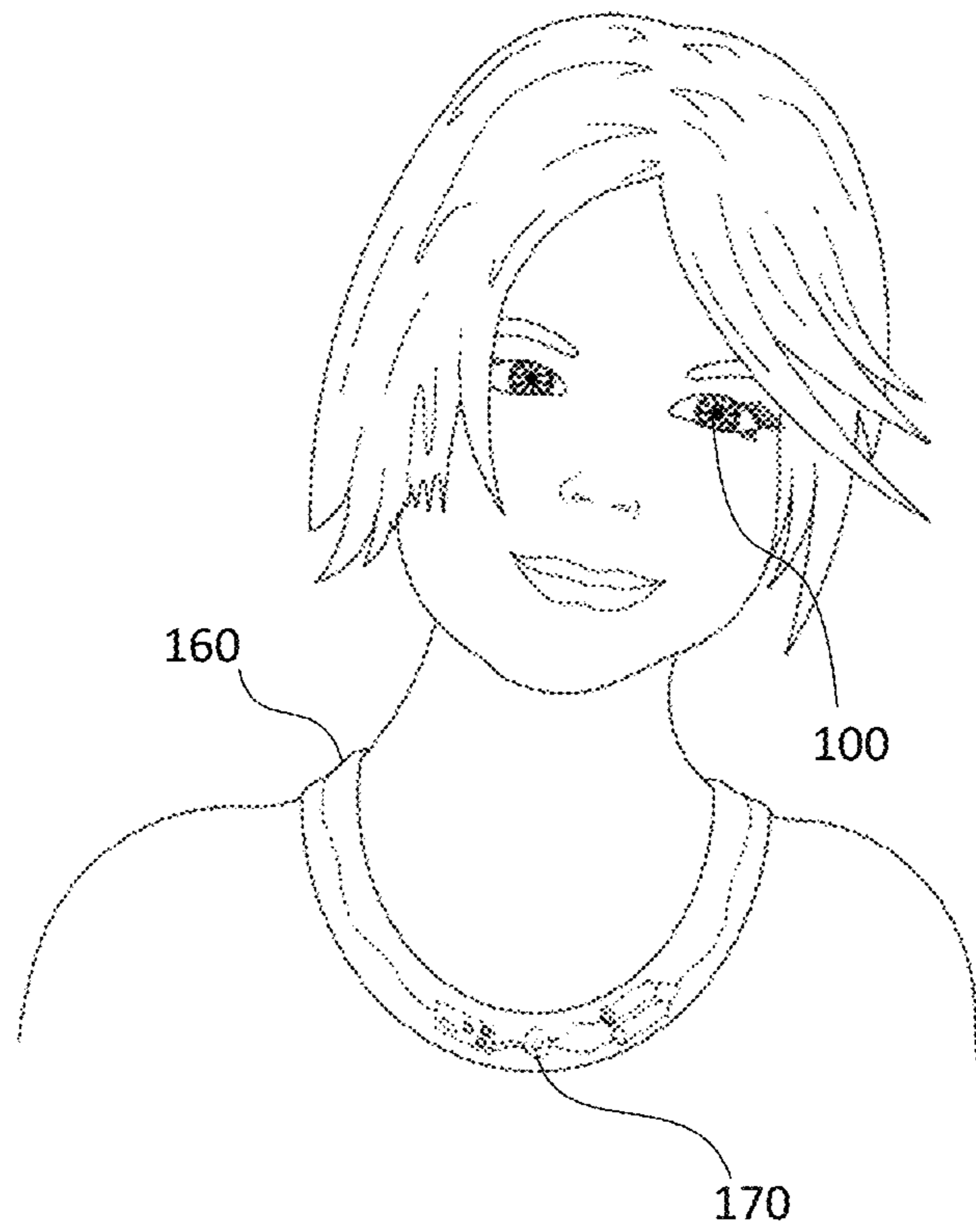


Fig. 1A

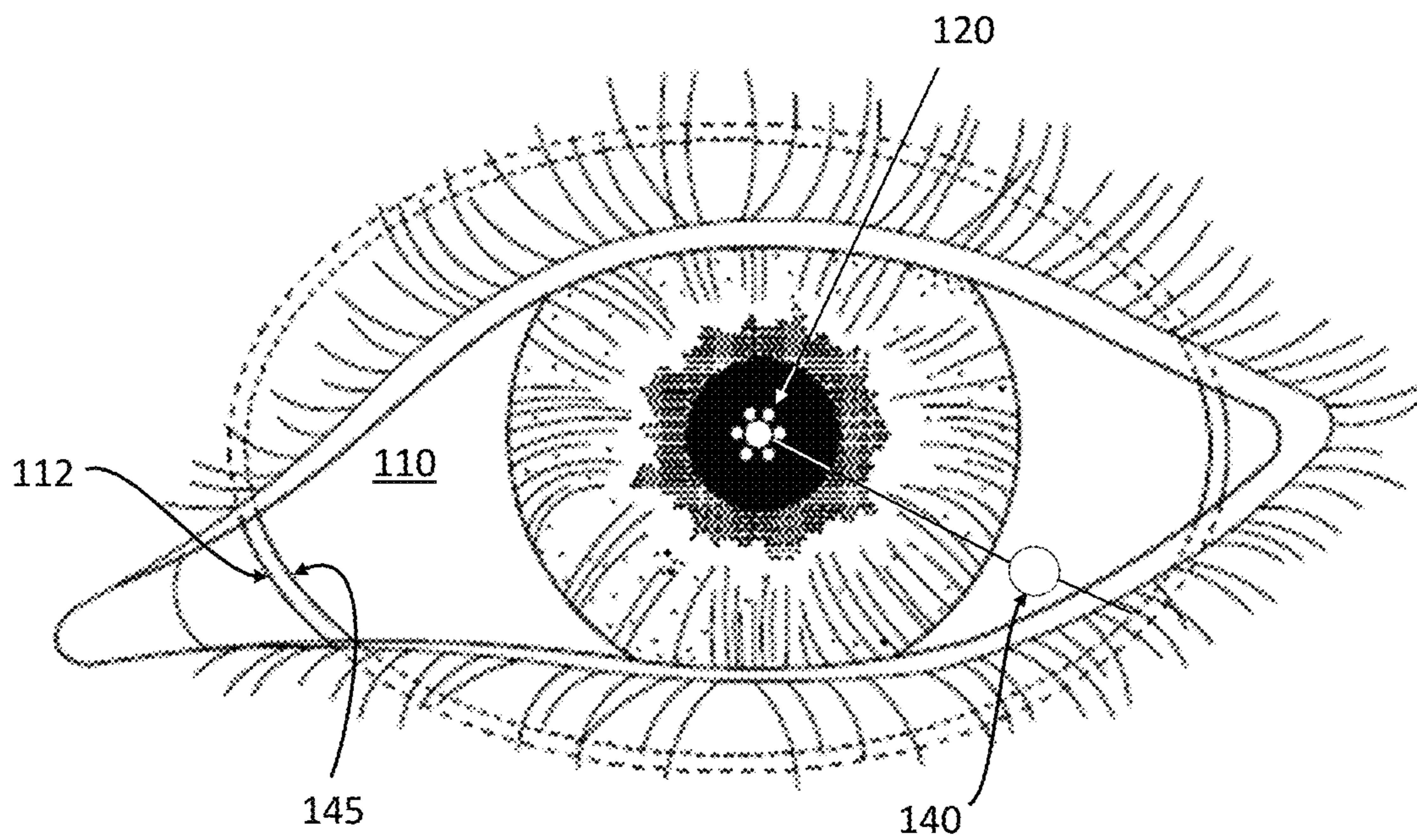


Fig. 1B

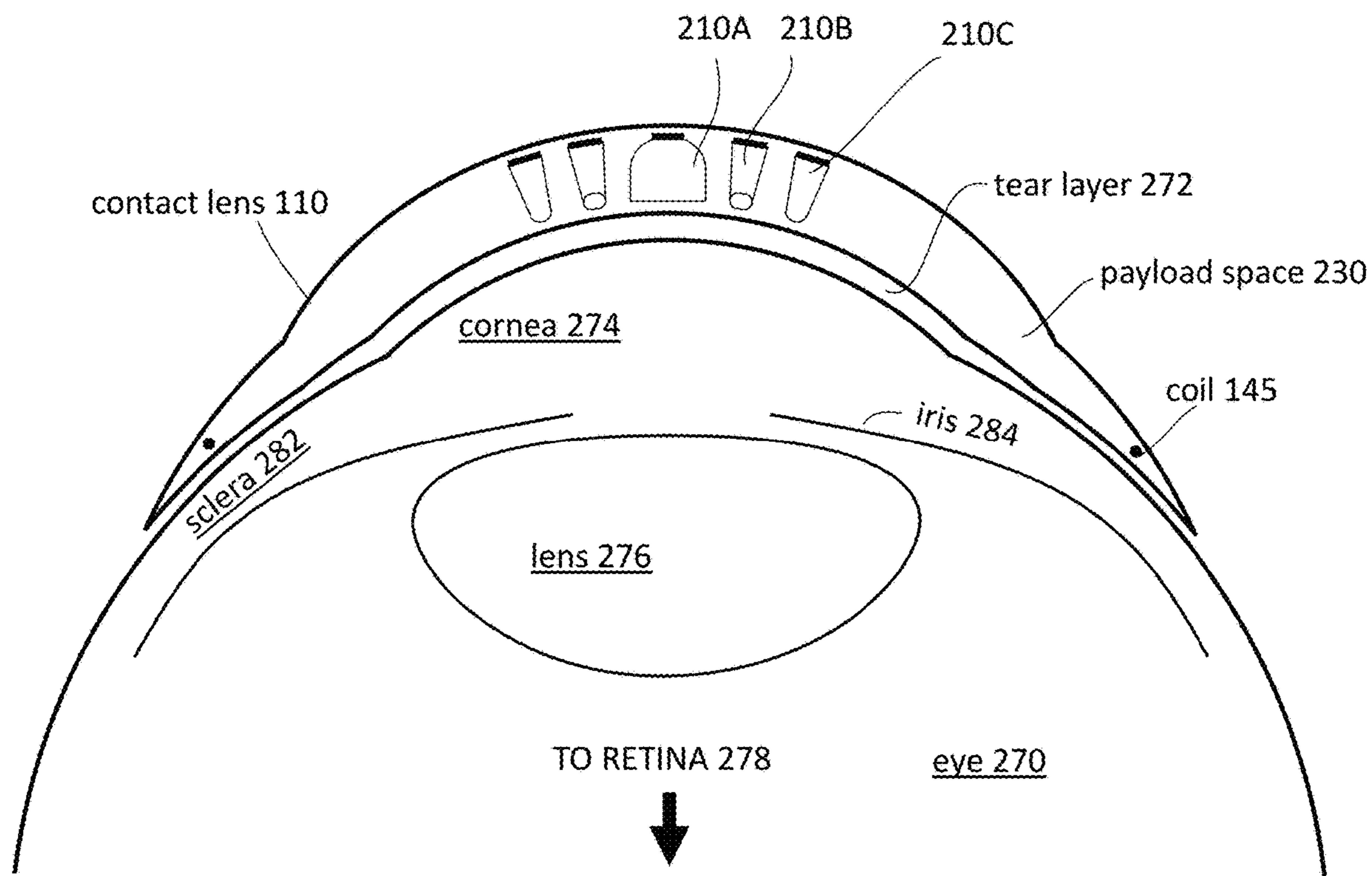


Fig. 2A

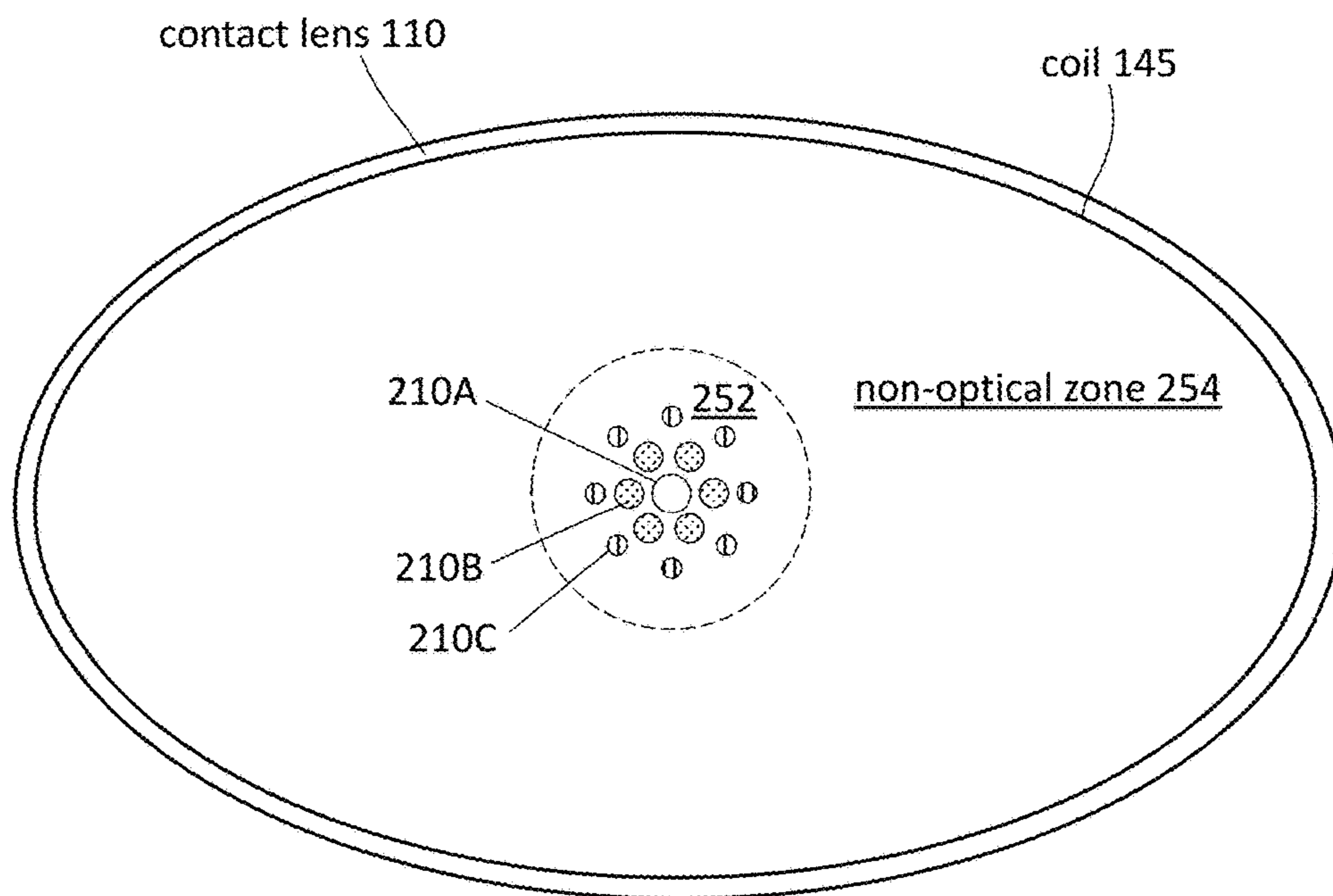


Fig. 2B

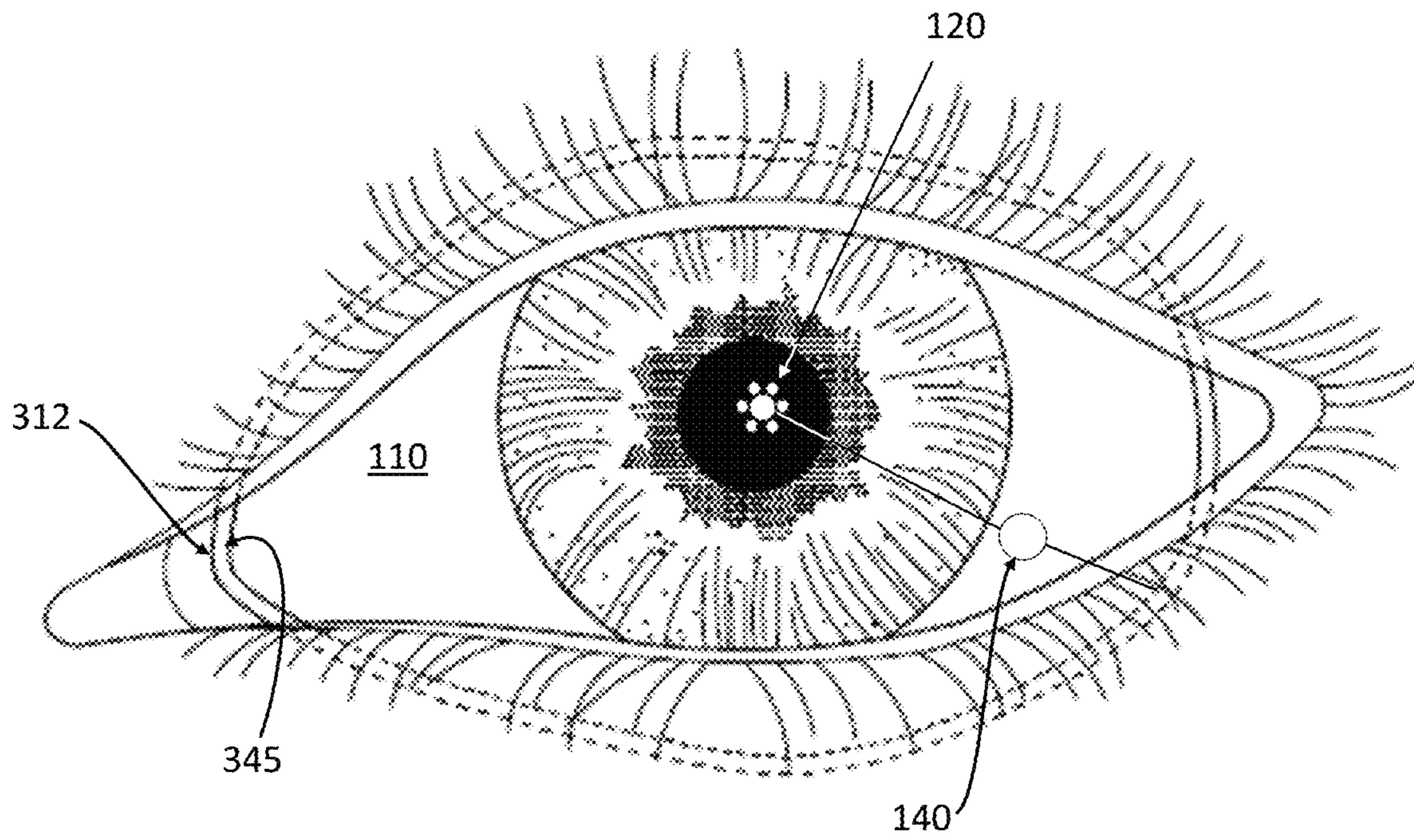


Fig. 3

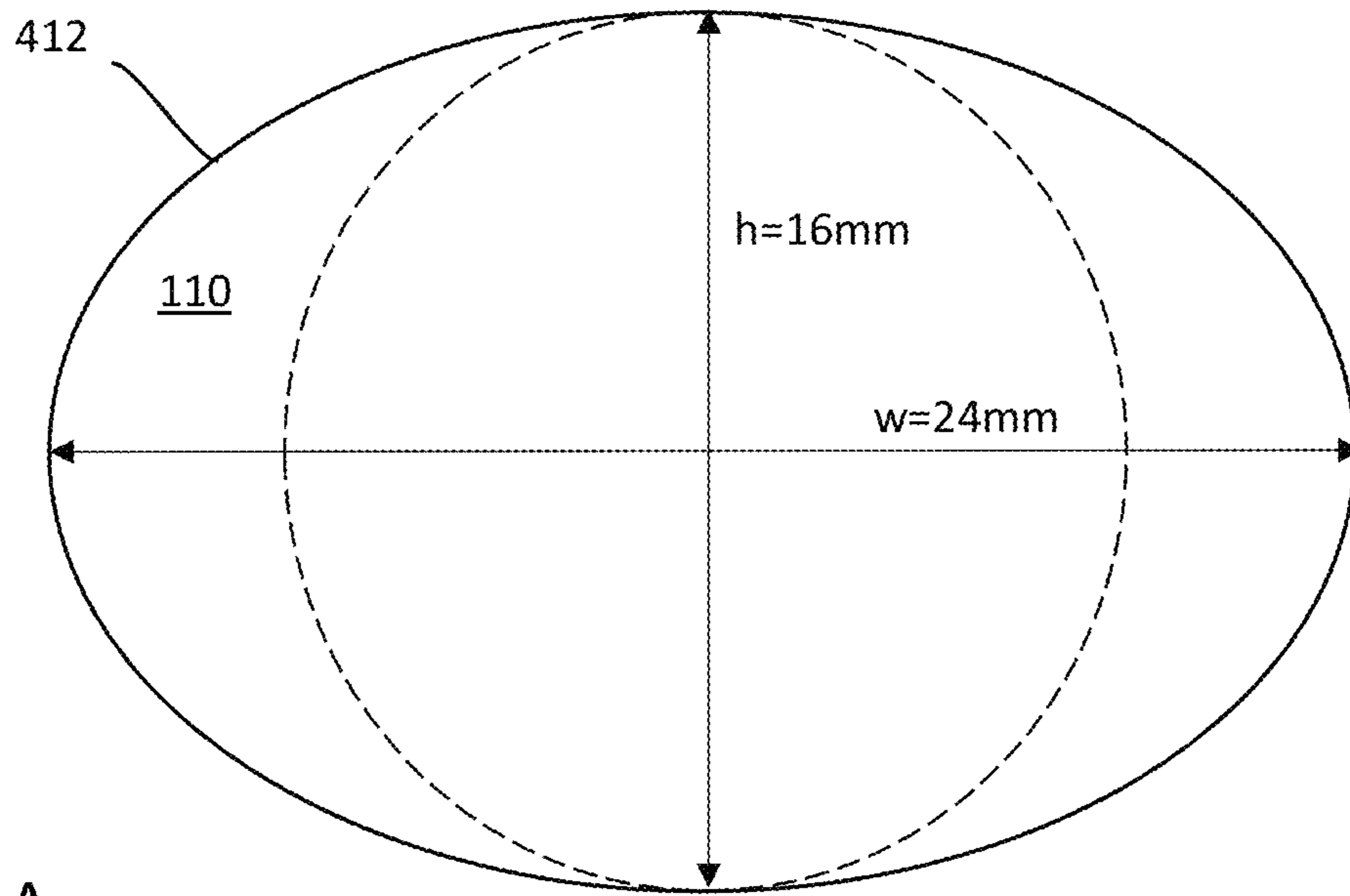


Fig. 4A

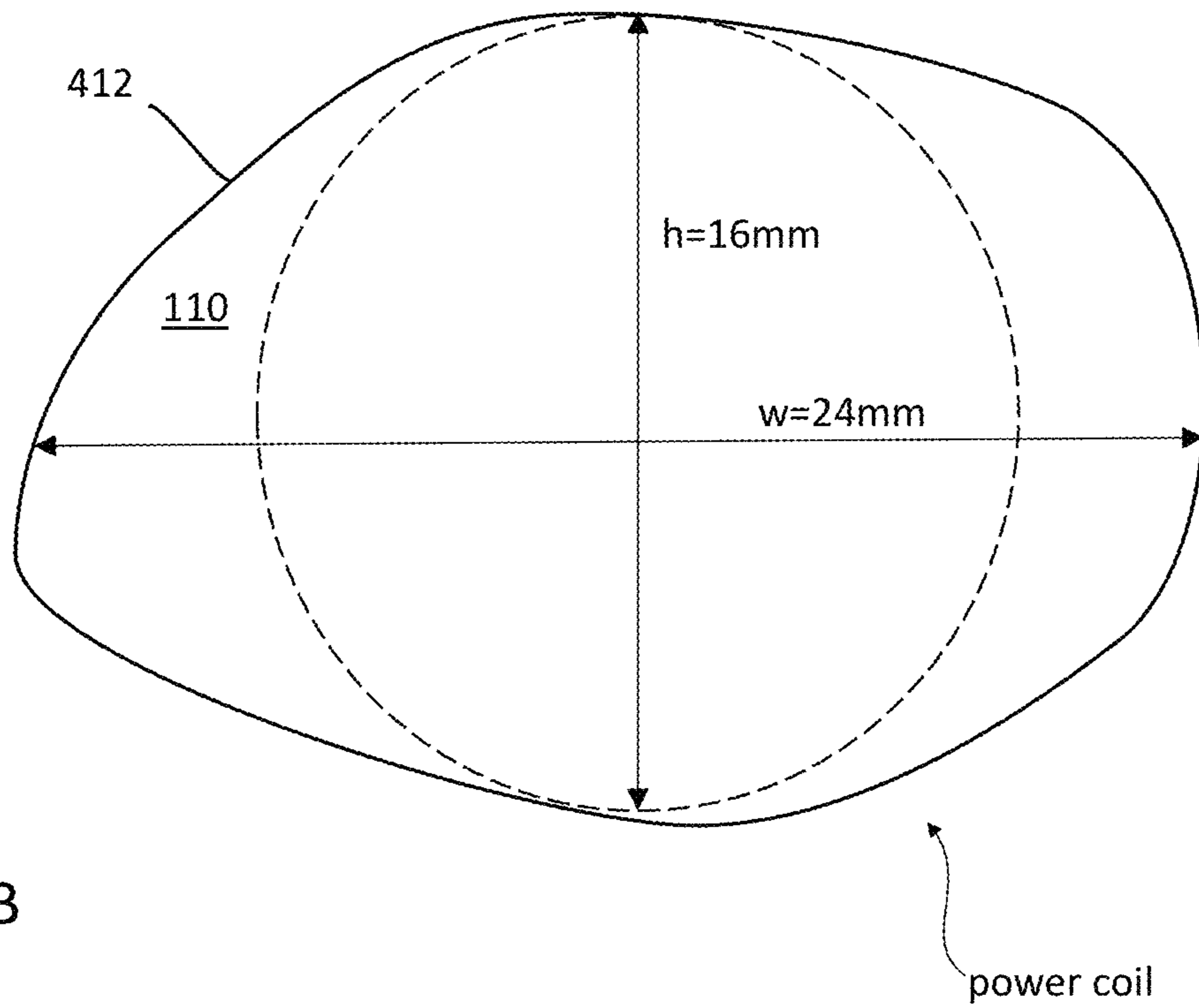


Fig. 4B



## NON-CIRCULAR CONTACT LENSES WITH PAYLOADS

### CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 15/955,844, filed Apr. 18, 2018, now U.S. Pat. No. 10,620,455, which is incorporated by reference in its entirety.

### BACKGROUND

#### 1. Technical Field

This disclosure relates generally to contact lenses with payloads, including for example eye-mounted displays.

#### 2. Description of Related Art

An eye-mounted display has been proposed by Deering. See, e.g. U.S. Pat. No. 8,786,675, "Systems using eye mounted displays." One type of eye-mounted display is based on a tiny projector mounted inside a contact lens. The projector projects images onto the retina of a person wearing the contact lens. The projector must be very small to fit in the contact lens, so small that Deering called it a "femtoprojector." A typical femtoprojector preferably is no larger than about one or two millimeters in any dimension.

Each femtoprojector in an eye-mounted display includes an image source and an optical system. A femtoprojector's optical system is designed to project images from the image source onto the retina so that the images appear in a person's field of vision. The femtoprojector optical systems are constrained to fit inside a contact lens while also providing appropriate magnification and sufficient image quality.

Eye-mounted displays can be used for virtual reality applications and also for augmented reality applications. In virtual reality applications, the images projected by the eye-mounted display replace what the user would normally see as his external environment. In augmented reality applications, the images projected by the eye-mounted display augment what the user would normally see as his external environment, for example they may appear as additions to the external environment. In both cases, it is usually important to project the images onto the user's retina with fairly high positional accuracy.

### BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the disclosure have other advantages and features which will be more readily apparent from the following detailed description and the appended claims, when taken in conjunction with the examples in the accompanying drawings, in which:

FIG. 1A shows a user wearing an eye-mounted display in communication with an auxiliary necklace.

FIG. 1B shows a magnified view of the eye-mounted display mounted on the user's eye.

FIG. 2A shows a cross sectional view of an eye-mounted display containing multiple femtoprojectors in a contact lens.

FIG. 2B shows a front view of an eye-mounted display containing multiple femtoprojectors in a contact lens.

FIG. 3 shows another eye-mounted display mounted on the user's eye.

FIGS. 4A and 4B show oval and irregular perimeters of contact lenses, respectively.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The figures and the following description relate to preferred embodiments by way of illustration only. It should be noted that from the following discussion, alternative embodiments of the structures and methods disclosed herein will be readily recognized as viable alternatives that may be employed without departing from the principles of what is claimed.

Contact lens devices that perform functions beyond just fixed vision correction may carry payloads in the contact lens, including electronic payloads. For example, an eye-mounted display may be based on a contact lens that contains one or more femtoprojectors and corresponding electronics. These displays project images onto the user's retina, which can provide an augmented reality and/or virtual reality to the user. There are many design challenges for such a device. For example, it is desirable to reduce or eliminate movement of the contact lens relative to the eye. If the contact lens slips or rotates on the eye, then the position of femtoprojector(s) in the contact lens will change relative to the retina. Mechanisms to compensate for this movement can make the overall system unnecessarily complex. Other challenges include efficiently transferring power and data to the contact lens and providing enough space within the contact lens for the electronic and other payload components.

In one approach, a scleral contact lens with a non-circular perimeter is used. A scleral contact lens rests on the sclera (i.e., the white part) of a user's eye. Elongating the scleral contact lens along the direction of the eye opening can result in a better fit between the contact lens and the eye. The elongated shape of the contact lens increases the area of contact between the contact lens and the user's sclera, thus reducing slippage and/or rotation of the contact lens relative to the eye. The interior surface of the scleral contact lens (i.e., the part contacting the sclera) can also be customized to match the contour of the user's eye, thus allowing a better fit between the contact lens and the user's sclera and further reducing contact lens movement relative to the eye. The non-circular shape also results in a larger perimeter, which can be used to accommodate conductive coils with a larger area, thus increasing coupling efficiency for power or data transfer. The non-circular lens can also provide more space within the contact lens for payloads.

In more detail, FIG. 1A shows a user wearing an eye-mounted display **100** in communication with a necklace **160**. FIG. 1B shows a magnified view of the user's eye and eye-mounted display **100**. The eye-mounted display **100** includes a contact lens **110**. The following examples use a scleral contact lens but the contact lens does not have to be scleral. The contact lens **110** has a non-circular perimeter **112** and extends below the upper and lower eyelids. In this example, the contact lens **110** has an "oval" perimeter **112** that is elongated along the direction of the eye opening. Due to the curvature of the eye, the actual shape of the perimeter is three-dimensional. However, for convenience, it will be referred to as oval if the two-dimensional projection onto a plane is oval. Due to the size of the contact lens **110**, it is partially covered by the user's eyelids.

The contact lens **110** also contains multiple femtoprojectors **120**, each represented by a white circle in FIG. 1B. The femtoprojectors **120** project images onto the user's retina.



The contact lens **110** moves with the user's eye **100** as the user's eye rotates in its socket. Because the femtoprojectors **120** are mounted in the contact lens **110**, they also move with the user's eye. Some femtoprojector(s) may always project images to the fovea, and other femtoprojector(s) may always project images to more peripheral regions which have lower resolutions.

In this example, the contact lens **110** also contains electronics **140** and a conductive coil **145**. The coil **145** may be used to wirelessly transmit and/or receive power and/or data, for example via induction. To increase coupling to the coil **145**, it is desirable to increase the area enclosed by the coil. In this example, because the contact lens **110** is elongated, the conductive coil **145** has a larger area than would be the case for a conventional contact lens with a circular perimeter. To increase the area enclosed by the coil **145**, the coil may be located near the perimeter **112** and have a similar shape as the perimeter **112**, as shown in FIG. 1B. For example, the conductive coil **145** may be constructed so that it lies parallel to and within 0.3 mm to 3 mm of the perimeter **112** (e.g., the coil **145** lies within 2 mm of the perimeter **112**).

In other embodiments, the contact lens **110** includes a battery that supplies power to the femtoprojectors **120**. The electronics **140** may be used to control the femtoprojectors, receive or process images from the femtoprojectors, provide power to the femtoprojectors, and/or transmit data to/from the femtoprojectors. The contact lens **110** may also include other components.

FIG. 1A shows an implementation where, in addition to the eye-mounted display **100**, the user is also wearing a necklace **160** that contains components of the eye-mounted display system. In this example, the necklace **160** includes a wireless transmitter **170** that transmits image data and/or power to the eye-mounted display **100**. For an eye-mounted display, reducing the data transmission rate is desirable, both because the available bandwidth is limited and because it is desirable to reduce the complexity and power consumption of electronics in the contact lens.

FIG. 2A shows a cross sectional view of an eye-mounted display containing femtoprojectors **210** in a scleral contact lens **110**. FIG. 2B shows a top view, i.e., a view looking at the user's eye. In this example, there are three types of femtoprojectors **210A**, **210B**, and **210C**, which have different optical designs depending on the desired resolution and magnification. The retinal receptive fields are more densely packed towards the fovea and become progressively less densely packed away from the fovea. Accordingly, in one implementation, femtoprojectors that project to the fovea generate higher resolution images on the retina, and those that project to the periphery of the retina generate correspondingly lower resolution images.

The contact lens **110** is separated from the cornea **274** of the user's eye **270** by a tear layer **272**. Over the cornea **274**, the tear layer **272** may be as thick as a hundred microns or more while it may be only a few microns thick over the sclera **282**. The aqueous of the eyeball is located between the cornea **274** and the crystalline lens **276** of the eye. The vitreous fills most of the eyeball including the volume between the crystalline lens **276** and the retina **278**. The iris **284** limits the aperture of the eye.

The contact lens **110** preferably has a thickness that is less than 2 mm, and the femtoprojectors **210** each preferably fits in a 2 mm by 2 mm by 2 mm volume, or less. The contact lens **110** should be comfortable to wear and maintains eye health by permitting oxygen to reach the cornea **274**. In some designs, the optical paths from the image sources in

the femtoprojectors **210** to the retina **278** do not include any air gaps, although that is not required.

In FIG. 2B, the contact lens **110** is roughly divided by the dashed circle into an optical zone **252** and a non-optical zone **254**. Components in the optical zone **252** may be in the optical path of the eye, depending on how far open the pupil is. Components in the non-optical zone **254** fall outside the aperture of the eye. In addition to the femtoprojectors **210**, the contact lens may also contain other components for data transmission, power, and/or positioning. Data transmission components may include antennae or optical/infrared photodetectors, data storage and buffering, controls, and on-lens processing. Power components may include coils for power transmission and batteries for power storage. Positioning components may include accelerometers, gyroscopes, or other structures used for eye tracking and head tracking.

The use of a larger contact lens **110** can create more space **230** for components in the contact lens. In addition, the contact lens and its components can be colored to make them less visible to outside observers. For example, components that are positioned in front of the iris **284** can be made opaque with a color that matches the user's eye. Components that are in front of the sclera **282** may be given a white appearance or otherwise match the sclera. This allows components and the contact lens **110** to be less visible.

In addition to the eye-mounted display, the overall system may also include a head tracker, eye tracker, and scaler. The system receives input images (including possibly video), which are to be displayed to the human user via the eye-mounted display. The femtoprojectors **210** project the images on the user's retina, thus creating an image of virtual objects in the user's field of view. The scaler receives the input images and produces the appropriate data and commands to drive the femtoprojectors. The head tracker and eye tracker provide information about head movement/position and eye movement/position, so that the information provided to the femtoprojectors can be compensated for these factors.

There are many ways in which this functionality can be configured with an eye-mounted display(s) to create embodiments of eye-mounted display systems. Portions of these subsystems may be external to the user, while other portions may be worn by the user in the form of a headpiece or glasses. Components may also be worn on a belt, armband, wrist piece, necklace, or other types of packs. FIG. 1A shows an example where some functionality is implemented in a necklace **160** worn by the user.

The scleral contact lenses **110** can take various shapes, not just circular and oval. FIG. 3 shows another eye-mounted display mounted on the user's eye, where the perimeter **312** of the contact lens **110** has an irregular shape. The contact lens also contains a set of femtoprojector(s) **120**, various other components **140**, and a conductive coil **345**. In the drawing, the coil **345** follows the outline of the perimeter **312**, but it is not required to do so. For example, it may be more rounded to reduce corners in the conductive coil **345**.

FIGS. 4A and 4B show the perimeters **412** of the contact lenses **110** of FIGS. 1B and 3, respectively. The dashed line shows an inscribed circle. The sizes of the contact lenses **110** can be described by their width "w" and height "h." The height and width are equal for a circular contact lens. As seen in FIGS. 4A and 4B the width can be larger than the height. In the examples shown, w=24 mm and h=16 mm, for a w/h ratio=1.5. In some embodiments, the width w is between 10 mm and 30 mm and, similarly, the height h is between 10 mm and 30 mm. For example, the height h of the contact lens is at least 11 mm. In another example, the width



5

of the contact lens is at least 20 mm. In some embodiments, the perimeter **412** of the non-circular contact lens **100** has an enclosed area between 80 mm<sup>2</sup> and 800 mm<sup>2</sup>. In some embodiments, the shape of the perimeter **412** depends on available eye contour information.

In both FIGS. **4A** and **4B**, a conductive coil that follows the non-circular perimeter **412** of the contact lens **110** will enclose a larger area than a circular conductive coil that would also fit within the contact lens **110**. This larger area compared to a circular contact lens can result in more power transferred to the conductive coil, because voltage is proportional to the area and power is proportional to the square of the voltage. For example, consider FIG. **4A**. Assume the coil is 1 mm away from the perimeter. For a circular contact lens with a diameter of 16 mm, the conductive coil will have a diameter of 14 mm and an area of 154 mm<sup>2</sup>. The conductive coil for the elliptical contact lens in FIG. **4A** has major and minor axes of 22 mm and 14 mm, respectively. The enclosed area is 242 mm<sup>2</sup>, or about 60% greater induced voltage and about 150% more power than the circular contact lens.

A non-circular scleral contact lens **110** with an increased footprint can also be designed to include larger interior spaces for payloads (such as payload space **230** in FIG. **2A**), compared to a conventional circular contact lens. As a result, larger payloads or more payloads may be contained in the contact lens. In some designs, the payload space has a thickness of 1 mm or more (e.g., a thickness of at least 0.2 mm over an area of at least 10 mm<sup>2</sup>). Alternately, the payload space can have a volume of 300 mm<sup>3</sup> or more (e.g., a volume of at least 1 mm<sup>3</sup>).

Generally, the more scleral area that a lens covers and/or matches, the greater the lens stability and user comfort. Thus, in some implementations, non-circular contact lenses **110** are customized to increase the contact area with and/or to better fit the contour of a user's eye **120**. As such, the contact lens **110** may be aspheric and asymmetric. In some cases, a contact lens **110** is customized to increase the contact area with the user's sclera, for example by better matching the shape of the user's eye opening. In other cases, a contact lens **110** is customized to better match the interior surface of the contact lens to the contour of the eye. The interior surface of the contact lens **110** can be designed to grip the outside surface of the eye. These embodiments can further reduce contact lens **110** movement and rotation, resulting in increased positional stability of the contact lens and projected image relative to the eye.

To obtain a customized contact lens **100**, the contour of a user's eye may be measured. Techniques that measure the contour of the sclera may be advantageous because the contour information of the sclera (e.g., the area adjacent to the cornea) may be used to generate a well-fitting lens. For example, to enhance stability, the contact area between the contact lens and sclera may be at least 3 mm wide. Therefore, to design a customized contact lens, careful measurements of the sclera, and possibly a combination of multiple measurements of the sclera, may be used to construct a three-dimensional contour of the eye.

The contour of a user's eye can be measured using direct molding or by using structured light scanning, among other techniques. In direct molding, a mold of the user's eye contour is created by impressing the mold material directly onto the user's eye. The mold captures the contour of the eye and can be digitized (e.g., by scanning) to capture the relevant three-dimensional information. In structured light scanning, patterned light is projected onto the user's eye. The contour of the eye causes variations in the light pattern.

6

These variations can be captured and then used to reconstruct a three-dimensional contour of the eye.

The contact lenses **110** themselves can be shaped using a diamond lathe. The lathe can be equipped with multiple axes that are synchronized to spindle rotation in order to cut a customized asymmetric lens shape. For example, the lathe is a two axis continuous path contouring and edging lathe that directly machines the contact lenses.

The lens design can be carried out by a trained professional using the available three-dimensional eye contour information (e.g., from direct molding, structured light scanning or other types of optical topography). The lens shape can be non-circular and can be determined based on the available eye contour information. The interior surface of the contact lens can be shaped to fit the contour of the eye. In some cases, optical information relevant to the optical zone of the contact lens can be entered based on the user's needs (e.g., vision correction information). The final lens design can be generated based on this information and it can be reviewed by a trained professional before lens fabrication.

Although the detailed description contains many specifics, these should not be construed as limiting the scope of the invention but merely as illustrating different examples. It should be appreciated that the scope of the disclosure includes other embodiments not discussed in detail above. Various other modifications, changes and variations which will be apparent to those skilled in the art may be made in the arrangement, operation, and details of the method and apparatus disclosed herein without departing from the spirit and scope as defined in the appended claims. Therefore, the scope of the invention should be determined by the appended claims and their legal equivalents.

What is claimed is:

1. An electronic contact lens system comprising:

a scleral contact lens having an interior surface that rests on a sclera of a user's eye when the contact lens is mounted on the user's eye, the contact lens including an optical zone which is in an optical path of the user's eye, wherein:

the contact lens extends beneath an eyelid of the user's eye when the user is wearing the contact lens;

a two-dimensional projection of a perimeter of the contact lens onto a plane is non-circular, and a width of the contact lens is larger than a height of the contact lens; and

an electronic payload mounted in the scleral contact lens, where the contact area of the interior surface with the sclera is large enough to reduce slippage and rotation of the contact lens relative to the user's eye sufficiently for operation of the electronic payload.

2. The electronic contact lens system of claim 1 where a width of the contact lens is at least 20 mm.

3. The electronic contact lens system of claim 1 where the two-dimensional projection of the perimeter of the contact lens encloses an area of at least 80 mm<sup>2</sup>.

4. The electronic contact lens system of claim 1 where the electronic payload is mounted in an interior space of the contact lens, and the interior space has a thickness of at least 0.2 mm over an area of at least 10 mm<sup>2</sup> or has a volume of at least 1 mm<sup>3</sup>.

5. The electronic contact lens system of claim 1 where the interior surface that rests on the sclera of the user's eye has a contact area with the sclera that is at least 3 mm wide at one part of the perimeter.



7

6. The electronic contact lens system of claim 1 where the interior surface of the contact lens is customized to fit a contour of the sclera of the user's eye.

7. The electronic contact lens system of claim 6 where a shape of the perimeter is customized to the user's eye.

8. The electronic contact lens system of claim 7 where the contact lens is customized based on an available contact area with the user's sclera.

9. The electronic contact lens system of claim 8 where the contact lens is customized based on a shape of the user's eye opening.

10. The electronic contact lens system of claim 6 where the contour of the sclera of the user's eye is measured by direct molding or structured light scanning, and the interior surface of the contact lens is customized based on the measured contour.

11. The electronic contact lens system of claim 10 where the contact lens is manufactured into a customized aspheric shape using a multi-axis lathe.

12. The electronic contact lens system of claim 1, where the electronic payload comprises a femtoprojector mounted in the optical zone of the scleral contact lens, the femtoprojector configured to project images onto a retina of the user's eye, and the contact area of the interior surface with the sclera is large enough to reduce slippage and rotation of the contact lens relative to the user's eye sufficiently to stabilize the projected images on the user's retina.

13. The electronic contact lens system of claim 1 where the electronic payload further comprises an electronic com-

8

ponent mounted in a portion of the contact lens in front of the sclera and the electronic component is colored to match a coloring of the sclera.

14. The electronic contact lens system of claim 1 where the electronic payload further comprises an electronic component mounted in a portion of the contact lens in front of the sclera and the portion of the contact lens has an appearance that matches a coloring of the sclera and obscures the electronic component.

15. The electronic contact lens system of claim 1 where the contact lens is aspheric and asymmetric.

16. The electronic contact lens system of claim 1 where the two-dimensional projection of the perimeter of the contact lens has an oval shape.

17. The electronic contact lens system of claim 1 where the two-dimensional projection of the perimeter of the contact lens has an irregular shape.

18. The electronic contact lens system of claim 1 where the contact lens has a thickness less than 2 mm.

19. The electronic contact lens system of claim 1 further comprising a battery located in a non-optical zone of the contact lens and configured to power the electronic payload.

20. The electronic contact lens system of claim 1 where the electronic payload comprises an accelerometer and a gyroscope located in a non-optical zone of the contact lens, and the contact area of the interior surface with the sclera is large enough to reduce slippage and rotation of the contact lens relative to the user's eye sufficiently for operation of the accelerometer and the gyroscope relative to the user's eye.

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